LCA Methodology

Country-dependent Characterisation Factors for Acidification in Europe
A Critical Evaluation

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Abstract

Goal, Scope and Background. Country-dependent characterisation factors for acidification have been derived for use in life cycle assessments to describe the effect on ecosystem protection of a change in national emissions. They have recently also been used in support of European air pollution abatement policies and related cost benefit analyses. We demonstrate that the characterisation factors as calculated to date are unstable due to being derived from the non-smooth and highly varying part of the underlying emission-impact functions. The purpose of this paper is to discuss the currently available characterisation factors and to propose a modification that makes use of the full range of the underlying functions.

Method. The characterisation factors derived in this paper are based on updates of data used to support European air pollution agreements under the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP) and the European Commission. The focus in this paper is on the analysis of characterisation factors for acidification. The analysis of characterisation factors for terrestrial eutrophication from nitrogen compounds is a simple extension of the methods described here. The analysis is conducted for 25 European nations, i.e. for 23 EU countries plus Norway and Switzerland; Cyprus and Malta are excluded due to lack of data on critical loads.

Results and Conclusions. We show that a linear model which is calibrated to emission changes of –50% is generally more reliable than characterisation factors which are based on emission changes of plus or minus 10%. Application of these characterisation factors are justified for emission reductions up to 30% in total European emissions, compared to 2000. This is within the range of currently agreed upon emission reductions in 2010 relative to 2000. Therefore, characterisation factors can be used in LCA as well as for the support of the revision of existing European air pollution agreements.

Keywords: Acidification; air pollution; critical loads; integrated assessment modelling; life cycle impact assessment

Introduction

In recent years, country-dependent characterisation factors have been proposed as an alternative to the conventional hydrogen release potentials in life cycle impact assessment (Hauschild & Potting 2003, Guinée et al. 2002, Udo de Haes et al. 2002). These factors of Huijbregts et al. (2000), Krewitt et al. (2001), Potting et al. (1998a,b) quantify the impacts caused by marginal changes in SO_2, NO_x and NH_3 emissions in European countries. The characterisation factors of Krewitt et al. (2001) and Potting et al. (1998a,b) establish a linear relationship between changes in European ecosystem protection and a change in the emissions of sulphur or nitrogen compounds in one country (with emissions in all other countries remaining unchanged).

The characterisation factors of Potting et al. (1998a,b) and Krewitt et al. (2001) are of the same type, though derived from different integrated assessment models and different assumptions. Their factors have in common that they show a large variation between countries (a factor of 1000 between highest and lowest value). The value of a characterisation factor of a single country depends on (a) the reference year of the emissions, (b) the atmospheric transport model, and (c) the area and vulnerability of receptors or ecosystems. The characterisation factors of Potting et al. (1998a,b) and – thus implicitly also those of Krewitt et al. (2001) – have been criticised by Heijungs & Huijbregts (1999). They argue that characterisation factors cannot be robust because of the stepwise character of the cumulative distribution of ecosystem vulnerability. This could lead to instabilities of the characterisation factor, if based on a too small increment. Despite these potential instabilities, characterisation factors by Krewitt et al. (2001) are now increasingly used in applications to assess external costs of energy related activities (see, for example, European Commission 2003), and have also been applied to compute so-called 'avoidance costs' (Vermoote & de Nocker 2003). These avoidance costs are used as a surrogate for monetary assessments of changes in ecosystem protection caused by changes in country emissions. Characterisation factors used should be scientifically sound and sufficient knowledge of their reliability/uncertainty should be communicated with them, if they are to be trusted, e.g. in life cycle assessment studies or in cost benefit analysis of European air pollution policies.

This paper describes results of a systematic analysis to derive European characterisation factors for acidification and to test their robustness. Also, recommendations are made to delimit the usefulness of the characterisation factors for providing sound support to European air pollution policies.

1 Approach

The characterisation factors derived in this paper are based on updates of data used to support European air pollution agreements under the UNECE Convention on Long-range

Transboundary Air Pollution (LRTAP) and the European Commission. In particular, we use European databases of critical loads (Hettelingh et al. 2001, Posch et al. 2003), recent data on emissions of sulphur and nitrogen compounds for 2000 and 2010 (Schöpp et al. 2003), and source-receptor matrices for atmospheric transport derived from the EMEP Lagrangian model (EMEP 1998). Source-receptor matrices relate national emissions (the sources) to 150 x 150 km² grid cells covering Europe (the receptors), in which critical loads have been computed for about 1.5 million ecosystem sites. This detailed, modelled relationship between national emissions, depositions on EMEP grid cells, individual ecosystem critical loads is referred to as the "exact model" in the remainder of this paper.

The focus in this paper is on the analysis of characterisation factors for acidification. The analysis of characterisation factors for terrestrial eutrophication from nitrogen compounds is a simple extension of the methods described here. The analysis is conducted for 25 European nations, i.e. for 23 EU countries plus Norway and Switzerland; Cyprus and Malta are excluded due to lack of data on critical loads. The rest of Europe is treated as a 26th single emission area. The evaluation of ecosystems protection is conducted within the same area of Europe.

In this paper we explore the appropriateness of a linear model for the estimation of ecosystem protection, and the constraints under which it is justified to use characterisation factors. This would allow using linear relationships instead of more complex models such as the exact model used in this paper, the EcoSense model used by Krewitt et al. (2001) and the RAINS model (Amann et al. 1999) used by Potting et al. (1998a,b). We write the linear approximation to the exact model as follows:

$$A(e_1, e_2, ..., e_{3N}) = A_{2000} + \sum_{i=1}^{3N} p_i e_i \qquad (1)$$

where A is the area (km²) of unprotected ecosystems in Europe, A_{2000} the area of unprotected ecosystems due to emissions in 2000, e_i the emission change (kt) of SO_2, NO_2 or NH_3 in region i (hence $3N$ combinations of N=26 emissions) and p_i the characterisation factor (km²/kt) of region i. Note that the e_i are negative for emission reductions.

If results of the linear model were the same as those of the exact model, the characterisation factors would be independent of the choice of the reference year of emissions, the sign and magnitude of an emission increment, and the influence of emission reductions in the other countries. This hypothesis of linearity is explored in four steps:

1. First we investigate the linearity and the importance of the choice regarding the magnitude and sign of emission changes.
2. Next we suggest a calibration procedure to derive reasonably stable characterisation factors.
3. Then we explore the performance of the linear model by looking at emission reductions in all regions.
4. Finally, we test the robustness of the linear model for a set of random combinations of emission reductions.

For each of these steps, the used methods and results are described in a separate sub-section.

1.1 Method and results – Linearity and choice of increment

In this section we analyse the sensitivity of characterisation factors p_i (see equation 1) with respect to the magnitude and sign of the emission change. Krewitt et al. (2001) computed the characterisation factor for country i for an emission increase of 10% (e_i = +10%), assuming no emission changes in the remaining countries. Potting et al. (1998a,b) worked with a negative increment, i.e. e_i = –10%, because this reflects the reality of reducing national emissions as a result of European air pollution policies.

We use the exact model to compute p_i from a change in unprotected ecosystems relative to a wide range of emission changes. This is done by changing the 2000 emissions of country i for a single pollutant in steps of 1% between –100% to +20%, leaving the emissions of the other pollutants and all emissions in other countries unchanged (i.e. –100% ≤ e_i ≤ +20%, i=1,…,3N and e_j=0 for $j \neq i$). Some examples are shown in **Fig. 1**, illustrating the sensitivity of $p_i = dA/de_i$ for emission changes of the three pollutants. Note that the change of emissions in Fig. 1 is expressed as percentage, while the change in unprotected ecosystem is expressed as km²/kt. Every dot in Fig. 1 (and in other figures in this paper) corresponds to a result derived from the exact model. It can be seen that changes in (un)protected ecosystem area are highly variable in most cases for emission changes between –20 and +20%, due to the fact that the spatial resolution of models as used by Potting et al. (1998a,b), Krewitt et al. (2001) and as in this paper are not high enough to allow evaluations of smaller changes. For emission changes between –100% and –20%, changes in unprotected ecosystems (dA/de) are by large constant, with the exception of Sweden. Within this range, the size of the increments does not seem to be important, which indicates the appropriateness of using a linear approximation to the exact model. The use for emission changes around the origin may not be justified for all applications (see next section).

1.2 Method and results – Calibration procedure

The result from the previous section leads to the following approach for calibration of the characterisation factors p_i The change of unprotected ecosystem area, A–A_{2000}, is computed by inserting distinct combinations of national emission changes in equation 1. First we let the linear relationship be exact for the 2000 emissions, i.e. for zero emission change, yielding the constant A_{2000} in equation 1. Then A is calculated with the exact model by reducing the emissions in country i with 50% (e_i = –50%), while the emissions in other countries are kept unchanged (e_j=0; $j \neq i$; j=1,..,3N). This is used to calculate the slope p_i of the linear function between A_{2000} and A as a characterisation factor for country i. We then compare the resulting lines with the exact model computations of $A(e_1,…,e_{3N})$ for e_i equal to +10, –10, –30, –50, –70 and –90% with e_j = 0 ($j \neq i$; j=1,..,3N). This establishes for every country i how well exact model computations of changes in protected area are approximated by the linear model. For comparison, characterisation factors are also calculated for e_i = +10% and e_i = –10% with e_j = 0 ($j \neq i$; j=1,..,3N) to mimic the calibration of published characterisation factors by Krewitt et al. (2001) and Potting et al. (1998a,b), respectively. **Fig. 2** illustrates the result of the above analyses for the same selection of countries as in Fig. 1.

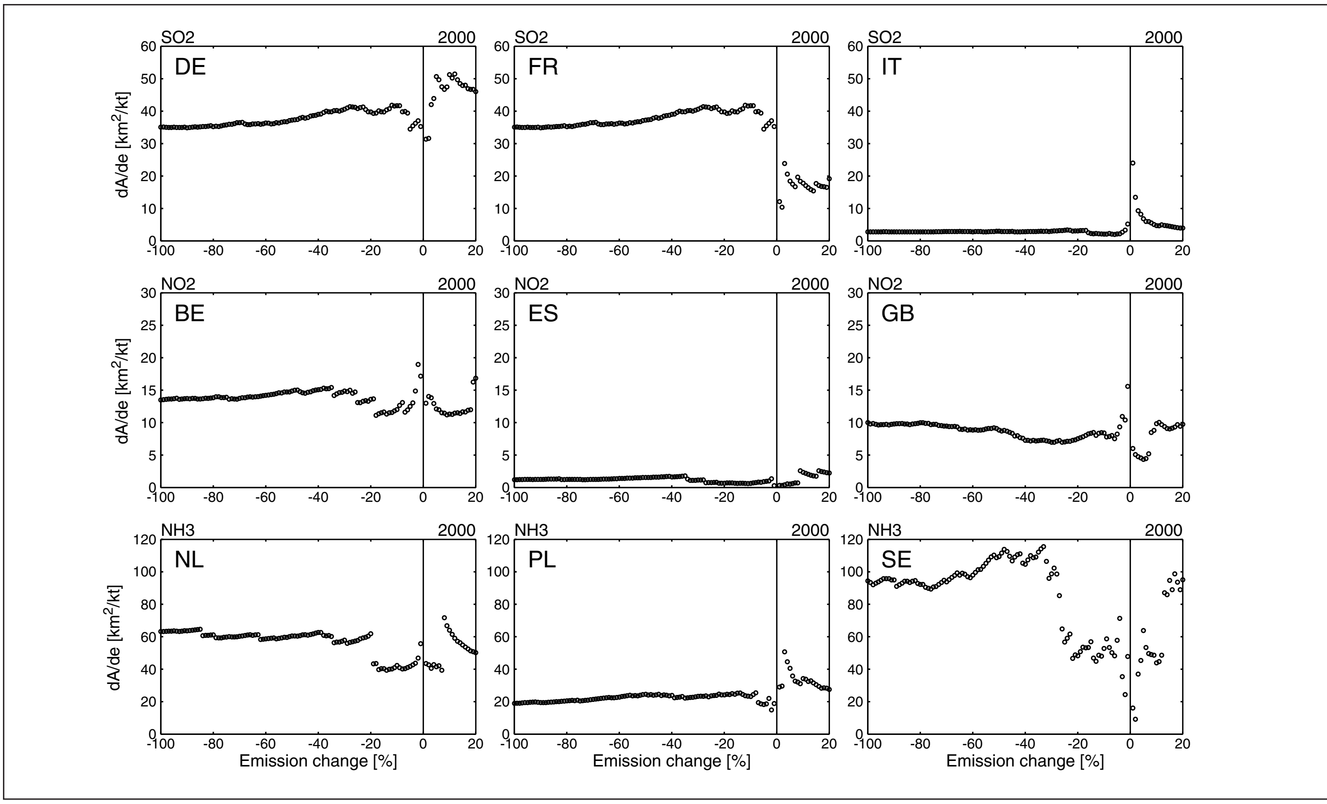

Fig. 1: Results of exact model computations of the characterisation factor p_i=dA/de_i (y-axis) caused by changes in emissions from –100% to +20% in steps of 1% (x-axis) of SO_2 in Germany, France and Italy (upper 3 graphs), of NO_2 in Belgium, Spain and the United Kingdom (middle), and of NH_3 in the Netherlands, Poland and Sweden (bottom)

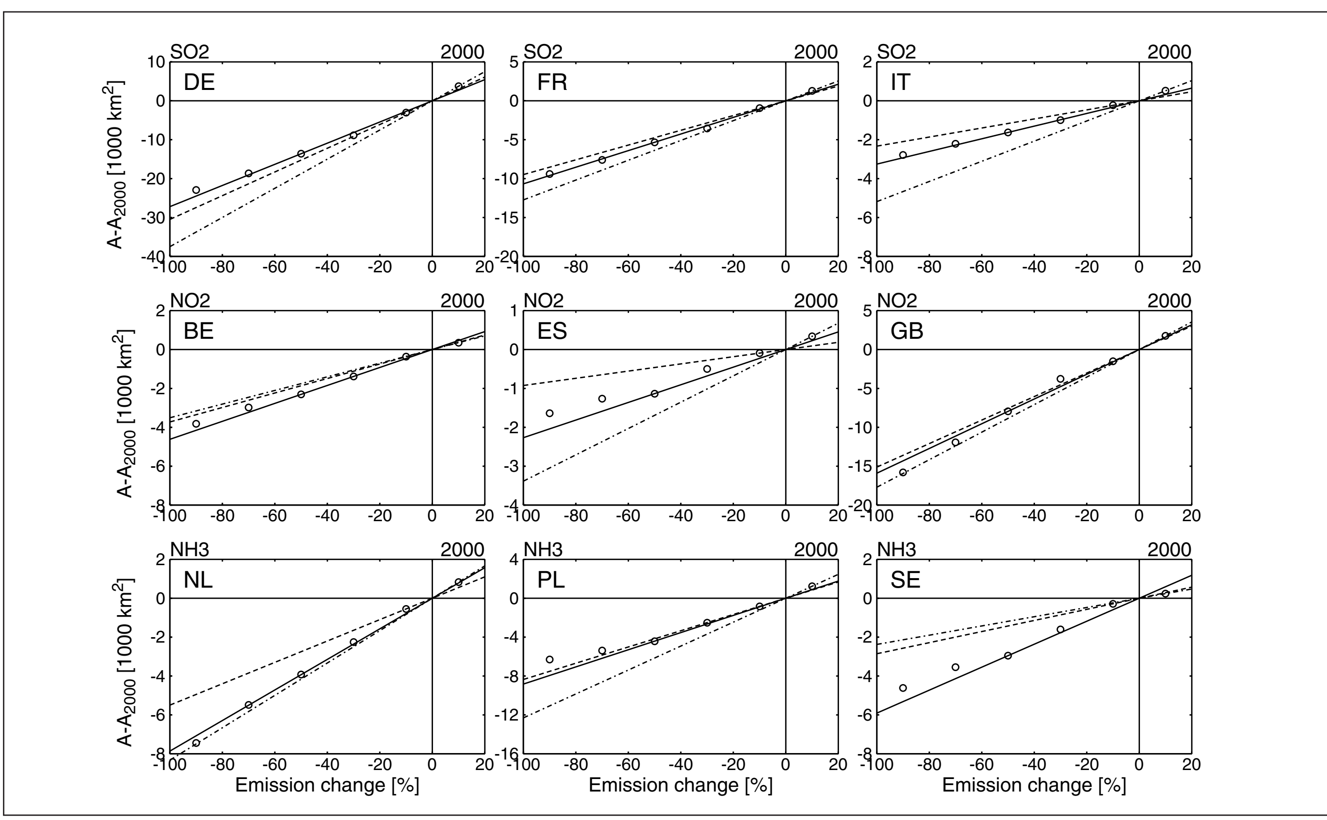

Fig. 2: Linear approximations (solid line through e = –50%; dashed line through e = –10% and dashed-dotted line through e = +10%) to the change in unprotected ecosystem area (in 1000 km²) for emission changes from the 2000 emissions of SO_2 (top), NO_2 (centre) and NH_3 (bottom) for nine countries (note the different scales on the y-axes). The open circles indicate values computed with the exact model

Table 1: European characterisation factors for acidification computed for 2000 emissions of SO_2, NO_2 and NH_3. A_{2000}, the total European ecosystem area unprotected in 2000, is 265,370 km²

2000	SO_2			NO_2			NH_3		
Country *i*	Emission kt	p_i km²/kt	abs.error[a] km²	Emission kt	p_i km²/kt	abs.error[a] km²	Emission kt	p_i km²/kt	abs.error[a] km²
Austria (AT)	45	21.67	19.1	177	7.52	29.7	57	76.69	43.3
Belgium (BE)	165	27.35	49.9	310	14.89	58.8	97	39.54	134.5
Switzerland (CH)	30	11.86	40.3	123	5.44	46.4	69	17.81	55.0
Czech Rep. (CZ)	306	31.38	89.0	379	11.79	25.2	66	68.65	79.6
Germany (DE)	731	37.22	402.5	1486	16.14	163.9	511	78.54	745.8
Denmark (DK)	55	27.62	37.7	197	10.97	58.8	83	24.86	39.2
Estonia (EE)	80	16.81	86.1	45	1.50	10.1	8	7.75	7.5
Spain (ES)	1273	2.46	87.1	1446	1.57	120.9	379	1.94	67.8
Finland (FI)	101	23.99	87.9	206	3.31	15.3	44	31.68	66.8
France (FR)	717	14.89	157.4	1485	7.63	87.0	671	23.00	396.9
United Kingd. (GB)	1175	13.91	327.6	1798	8.84	455.1	378	28.64	84.9
Greece (GR)	504	0.19	13.2	359	0.24	10.0	55	1.15	8.6
Hungary (HU)	658	9.25	46.6	190	4.94	40.6	78	8.46	17.9
Ireland (IE)	147	13.49	76.5	151	8.82	48.3	119	24.71	49.4
Italy (IT)	1096	2.97	73.6	1442	1.49	62.9	462	3.58	62.4
Lithuania (LT)	34	4.82	45.6	71	4.23	46.1	29	3.79	62.2
Luxembourg (LU)	4	46.50	6.0	34	15.22	14.1	5	62.28	7.0
Latvia (LV)	18	11.01	8.8	46	1.59	10.8	12	14.28	12.5
Netherlands (NL)	96	25.22	29.8	412	13.18	76.6	130	60.46	128.2
Norway (NO)	19	65.07	76.1	186	15.91	108.5	29	100.88	117.9
Poland (PL)	1562	19.52	341.4	1027	6.22	104.8	360	24.52	111.1
Portugal (PT)	259	1.78	57.9	457	0.62	10.5	70	2.25	9.3
Sweden (SE)	79	42.24	109.9	235	10.18	68.6	54	109.36	236.7
Slovenia (SI)	110	7.07	33.7	51	3.86	14.7	16	16.86	12.2
Slovakia (SK)	88	12.81	30.6	94	5.09	20.1	32	18.95	56.2
Rest of Europe	16890	6.35	4925.3	10768	1.90	276.2	2842	6.81	703.8

[a] computed as the average of the absolute differences between the exact and the linear model for e_i = –50% to +10% in steps of 1%. Note that this error is an absolute measure, independent of the magnitude of the emission changes.

Note from Fig. 2 that the linear model provides a reasonable fit to the exact model when p_i is calibrated to e_i = –50%. The overall fit is generally worse, when e_i = –10% or, more so, when e_i = +10% is chosen to calibrate p_i. Extreme cases are Spanish and Swedish characterisation factors for NO_2 and NH_3, respectively. For example, a Spanish NO_2 emission reduction of 70% leads to an overestimation of unprotected ecosystem area by about 1000 km² and less than 350 km² when p_i is calibrated to e_{Spain} = +10% and e_{Spain} = –50%, respectively. When calibrated to e_{Spain} = –10% the reduction of unprotected ecosystem is underestimated by about 1 km²/kt. When inspecting the Swedish characterisation factor for ammonia emission changes, one can see that calibration to e_{Sweden} = +10% and e_{Sweden} = –10% provides an underestimation of the actual reduction of unprotected ecosystems in Europe of more than 20 km²/kt for an emission change of –90%. In conclusion, it can be stated that p_i depends on the calibration point, but the calibration to e_i = –50% provides a better fit over a wider range of emission changes.

In **Table 1** the characterisation factors calibrated to e_i = –50% for all 26 emission regions and the 2000 reference emissions are given. These characterisation factors can be used to compute changes in ecosystem area protection caused by changes in emissions relative to the reference emissions of 2000 (Schöpp et al. 2003). To use the characterisation factors of Table1 for a different set of reference emissions, say $E_{t,i}$ (i=1,…,3N), one has to set in equation 1 e_i=x+$E_{t,i}$–$E_{2000,i}$ where x is the desired emission change (in kt). To obtain reliable results, the new emission data set should not differ too much from the emissions used to derive the p_is (see below). Note that the error given in Table 1 is an absolute measure (km²); therefore its relative importance diminishes with an increase in emission changes.

1.3 Methods and results – Exploring the performance of the linear model

To explore the performance of the linear model for emission changes in all countries we compute the change of European unprotected ecosystem area by applying emission reductions of 20, 40, 60, 80 and 100% to SO_2, NO_2 and NH_3 in all countries simultaneously. **Fig. 3** illustrates the resulting reduction of the unprotected ecosystem area in Europe computed with the linear model calibrations (solid, dashed and dashed-dotted as Fig. 2) and the exact model (open circles). It illustrates an increasing overestimation of protected ecosystem area as emissions are reduced below 30%. In fact, below about 50% overall reductions, the linear model estimates a larger area protected than possible. The unprotected ecosystem area in 2000 (A_{2000}) is 265,370 km², which is shown as a horizontal line in Fig. 3. The differences between linear model calibrations seem to matter less.

Note that current emission agreements for 2010 (e.g. the 1999 LRTAP Gothenburg Protocol and the European Commission's NEC Directive) entail reductions of about 22%, 20% and 0% for SO_2, NO_2 and NH_3, respectively, compared to 2000 emissions. These reductions are well within the range of emission reductions in which linear model results compare well to the exact model results, i.e. below 30% (see Fig. 3).

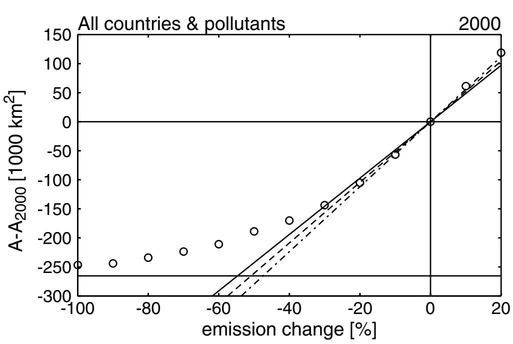

Fig. 3: The reduction of unprotected ecosystem area in Europe caused by emission changes in all 26 emission regions. The solid, dashed and dashed-dotted lines represent the results of the 3 different linear approximations (see Fig. 2). The dots reflect results of the exact model, showing that for up to 30% emission reductions there is good agreement between the models. The horizontal line at about –265 indicates the total ecosystem area unprotected in 2000 (in 1000 km²)

1.4 Method and results – Robustness of the linear model

Finally, the robustness of the linear model (equation 1) is tested by generating 200 emission scenarios and computing the area of unprotected ecosystems in Europe for each of them. This is done by randomly varying changes in SO_2 emissions between –70% and +30%, in NO_2 emissions between –50% and +30% and in NH_3 emissions between –30% and +30% in all of the 26 regions. A comparison between linear model results and the results computed with the exact model is shown in **Fig. 4**. The concentration of the

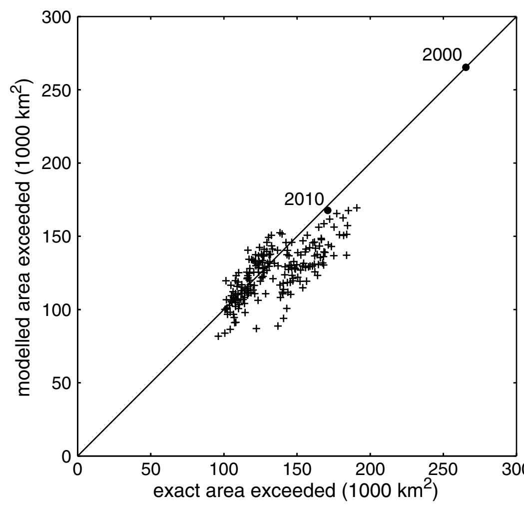

Fig. 4: The comparison of the results of 200 emission scenarios using the exact model (x-axis) and the linear model (y-axis) by randomly varying changes of SO_2 emission in each country between –70% and +30%, NO_x emissions between –50% and +30% and NH_3 emissions between –30% and +30%. Since characterisation factors have been calibrated to 2000 emissions, the protection in 2000 is identical for the linear and exact model. It is shown for 2010 projected emissions that the protected ecosystem area is very well computed by the linear model

results around the 1:1-line in a rather closely scattered cloud gives an impression of the maximum error one can expect when using the linear approximation (characterisation factors) instead of the exact model.

2 Discussion

Our analysis established that increments of –10% and +10%, as used by Potting et al. (1998a,b) and Krewitt et al. (2001), respectively, are not appropriate as calibration points for characterisation factors. The exact model used in this paper, the RAINS model as used by Potting et al. (1998a,b) and EcoSense as used by Krewitt et al. (2001) are not designed to evaluate small changes in emissions. The spatial resolution of these models, especially with regard to emission, atmospheric transport and deposition, is not high enough to allow such analyses. This raises the question whether it is justified to use the characterisation factors to assess the impact of small emission changes. The answer to this question is considered important for the impact assessment of the small changes by product systems as studied in life cycle assessment or new, individual technologies as studied by the European Commission (2003) and Vermoote and de Nocker (2003). Historically, in the field of systems analysis and mathematical modelling, this type of question depends on the manner in which system components are related (Simon 1978). The use in this paper of low-resolution totals such as (a) national emissions, rather than the reality of sector-dependent or plant-specific emissions, (b) country-to-grid source-receptor relationships, rather than the reality of individual emission trajectories, (c) depositions which are assumed to be homogeneously distributed in a large grid-cell rather than the reality of ecosystem dependent depositions,

and finally (d) yearly averages of emissions and depositions rather than time-dependent statistics, implies that only a so-called response surface is modelled (see e.g. Downing et al. 1985). Simon (1978) pointed out that if certain low-resolution aspects of a system are of interest it may be described by an appropriate aggregate model. The converse of this statement is not necessarily true. For example, if we make the emission changes too small, it seems not justified to apply the aggregate model, as exemplified by the size of the error made with the linear model in estimating the change in protected ecosystem area relative to the emission change (see Table 1).

The absolute error in estimating the change in protected ecosystem area may be expected to reduce, if based on models with a higher spatial resolution than our exact model. The question remains whether higher resolution models will also lead to a significantly different linear model (e.g. different characterisation factors).

The analysis in this paper focused on the evaluation of the robustness of characterisation factors, which describe the change in ecosystem area protection caused by the change in emissions in one country by one unit. A number of alternative characterisation factors, based on a different definition of the category indicator, are proposed in the literature on life cycle impact assessment methodology:

- Huijbregts et al. (2000) used the RAINS model to calculate so-called hazard indices for European countries that quantify the country-dependent change in deposition divided by the critical load of receptors.
- Bare et al. (2003) quantified, for each of the federal states in the USA, the share of emission depositing on land with help of atmospheric fate and transport modelling (Shannon 1996) to account for expected source-location-dependent differences in wet and dry deposition.
- Pleijel et al. (1997) proposed characterisation factors based on the amount or share of emission depositing on ecosystems for which the critical load is exceeded. These factors were calculated for a limited number of Swedish regions and European countries with help of the EMEP model and critical load maps.

The characterisation factors of Pleijel et al. (1997) have been calculated for a few regions/countries only, and these factors and those of Huijbregts et al. (2000) and Bare et al. (2003) were quantified with a different modelling framework than ours. The factors as proposed by Pleijel et al. (1997) are of special interest, because they are based on an indicator definition similar to average accumulated exceedance (see Posch et al. 2001), which has been used in support of European emission reduction policies. Also average accumulated exceedance is based on complex, curvilinear relationships. This paper brought to bear that assumptions about linearity need to be carefully explored before using parameters such as characterisation factors and factors based on other indicator definitions. It is recommended that alternative characterisation factors, e.g. based on critical load exceedance measures, undergo similar careful considerations. This could enable one to evaluate whether country-dependent variation between characterisation factors are consistent across different category indicators and, when focussing on policy applications, contribute to the ongoing discussion in life cycle assessment about the preferred category indicator.

We calculated characterisation factors for emissions of SO_x, NO_x and NH_3. Hydrogen release potentials, which are used in conventional life cycle assessment, are also available, for example, for HF, HCl, H_2S, HNO_3 and H_3PO_4. These emissions hardly play a role on a national and European level, and are therefore not covered by our exact model. Therefore, we are unable to calculate characterisation factors for these substances.

Our characterisation factors relate to European nations only. The processes involved in life cycle assessment of product systems may take place all over the world. This causes limitations for the applicability of our characterisation factors. Hauschild and Potting (2003) propose to use the European (average) characterisation factor as a best estimate for processes taking place in unknown or non-European locations. We recommend exploring the appropriateness of this approach, for instance by calculating characterisation factors with an appropriate Asian version of an exact model.

3 Summary and Conclusions

Characterisation factors for acidification have been derived for 26 European regions. These have been obtained by deriving a linear approximation of the relationships between emission changes and changes in protected ecosystem areas. These relationships use information on national emissions, source-receptor relationships and a European data base on critical loads. Results of the linear model were compared with this exact model showing that characterisation factors are relatively sensitive to the emission changes against which they are calibrated. We show that a linear model which is calibrated to emission changes of –50% is generally more reliable for use in support of European air pollution abatement policies than characterisation factors which are based on emission changes of plus or minus 10%. Application of these characterisation factors is justified for emission reductions up to 30% in total European emissions, compared to 2000. This is within the range of currently agreed upon emission reductions in 2010 relative to 2000. Therefore, characterisation factors can be used for the support of the revision of existing European air pollution agreements.

4 Recommendations

The application of linear approximations of exact models used in integrated assessment may expedite the analysis of the impact of individual country emissions on the protection of ecosystems in Europe. Whether this conclusion can be generalised to other well-known indicators used in the support of European air pollution policies, such as the average accumulated exceedance, requires further work. The follow-up question on the reliability of such simplified indicators in the assessment of cost benefit analysis, for example, requires a comprehensive understanding of possible error propagation. To begin with, careful consideration is required of the fact that critical loads are not based on dose-response relationships. Therefore, further research is needed to justify the use of characterisation factors based on critical loads as a surrogate for dose-response relations.

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Country-specific Damage Factors for Air Pollutants

A Step Towards Site Dependent Life Cycle Impact Assessment

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Abstract. An integrated impact assessment model is used to calculate the impact per tonne of SO_2, NO_x, fine particles, and NMVOC emitted from different source countries on human health, acidification, eutrophication, and the man-made environment (crop yield and building materials). Indicators on the endpoint level are used to measure the effects resulting from a marginal change in emission levels. While the assessment of impacts on ecosystems and the man-made environment is limited to Europe, damage factors for health effects are also derived for Asia and South America. For Europe, emission scenarios for the years 1990 and 2010 are considered to analyse the influence of changing background conditions on the resulting impacts. Results show that there is a significant variation in the damage resulting from a unit emission for some of the impact categories, both between countries and between base years. Depending on the scope of the study and the information available from the life cycle inventory, results from the paper can be used to consider site dependent conditions in life cycle impact assessment as a complement to the current site-independent (or global) approach.

Keywords: Acidification; air pollution; eutrophication; integrated impact assessment modelling; Life Cycle Assessment; Life Cycle Impact Assessment; site dependent impact assessment; Years of Life Lost